



University  
of Glasgow

# HIGH FREQUENCY COMMUNICATION SYSTEMS

## Lecture 1

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**PRELIMINARY INFORMATION**

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## COURSE TEAM



(a) Dr Qammer H Abbasi



(b) Dr Hasan T Abbas

## MOTIVATION - CHANG'E NO. 4



Panoramic View of the Chang'e No. 4 Lander on the Moon.

- We will award the best students for best overall performance and best project.



(c) Overall Prize



(d) Project Competition

- Introduction to Millimetre wave (mmWave) and Terahertz (THz) Frequency Communication Systems
- Theory of Electromagnetic (EM) wave propagation
- Channel Modelling Schemes
- Antenna Analysis & Design

- State of the art of electromagnetic simulation strategies for THz devices
- Application of solid-state structures and novel 2D materials in mmWave and THz device technologies
- Antenna design with emphasis on phased arrays used for beamforming
- Wireless Propagation models of mmWave and THz communication channels

At the end of the course you will be able to:

1. Recognise the physical limitations of electromagnetic wave propagation and the need to move to higher frequencies in next generation mobile communication.
2. Analyse the wireless channel models to characterise a cellular communication environment.
3. Use electromagnetic simulation techniques to study antennas and wave propagation.
4. Design complex antenna systems with specific beamforming needs for mobile environments.

## COURSE ASSESSMENTS

Assessment	Weightage
Homework	30%
Final Exam	30%
Term Project	30%
Class Participation	10%

## COURSE ASSESSMENTS DETAILS

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Homework	3 Assignments in total
Final Exam	2 Questions – 1 hour long
Term Project	Design a mmWave Cubesat antenna
Class Participation	Attendance and participation in the discussions

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## YOUR FIRST TASK

- Make a project plan for the mmWave Cubesat antenna
- You will be marked individually but are welcome to work as a team
- Prepare a Gantt chart for the project
- Come up with an expected budget of the project
- You can work in groups of 2 or 3

## THE RADIO SPECTRUM

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# DESCRIPTIONS

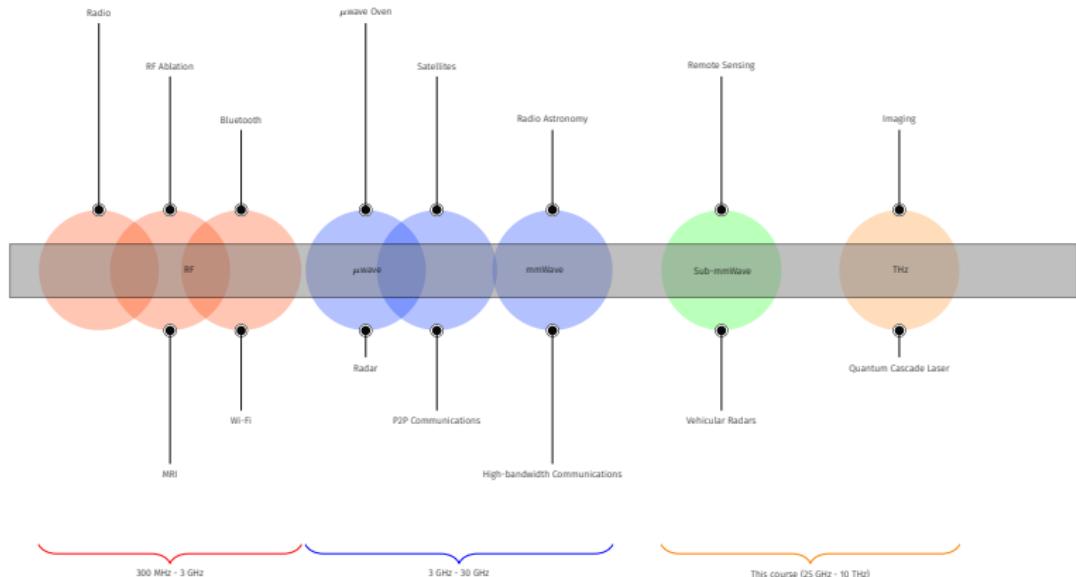


Figure 1: The electromagnetic wave spectrum

- EM theory deals with the study of charges
- Charges at rest or more importantly in motion

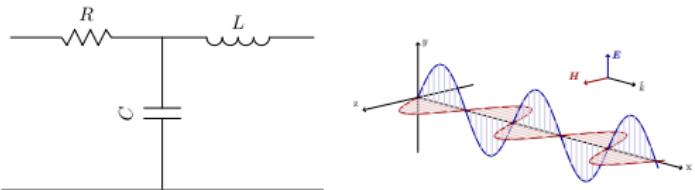


Figure 2: Circuit and Electromagnetic Theories

- Circuit theory is actually a subset of EM theory
- We apply *lumped* circuit theory when wavelength  $\lambda$  is much larger than circuit dimensions
  - Parasitic elements are negligible

## THE MAXWELL'S EQUATIONS

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- Set of four linear equations
  - Linearity helps multiple users access one radio link (tower).
- James Clerk Maxwell predicted wave propagation (1866)
- Heinrich Hertz (1886) experimentally proved the results in a lab
- Kick-started radio wave communications
- Comprehensive in explaining EM phenomena

- We use this form to describe the fields *at any point in space and time.*
- We call them field equations
- Widely used to solved wave phenomena.

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t} - \vec{\mathbf{M}} \quad (\text{Faraday's Law})$$

$$\nabla \times \vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t} + \vec{\mathbf{J}} \quad (\text{Ampere's Law})$$

$$\nabla \cdot \vec{\mathbf{E}} = \rho_e / \varepsilon_0 \quad (\text{Gauss' Law})$$

$$\nabla \cdot \vec{\mathbf{H}} = \rho_m / \mu_0 \quad (\text{Flux Law})$$

- The current density,  $\vec{\mathbf{J}} = \vec{\mathbf{J}}_i + \vec{\mathbf{J}}_d + \vec{\mathbf{J}}_c$
- In statics,  $\frac{\partial}{\partial t}$  is zero.

- We use this form to describe the fields over *an extended region of space.*
- Not widely used.

$$\oint_C \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t} \iint_S \vec{B} \cdot d\vec{S} \quad (\text{Faraday's Law})$$

$$\oint_C \vec{H} \cdot d\vec{l} = \iint_S \vec{J} \cdot d\vec{S} + \frac{\partial}{\partial t} \iint_S \vec{D} \cdot d\vec{S} \quad (\text{Ampere's Law})$$

$$\iint_S \vec{D} \cdot d\vec{S} = \iiint_V \rho_e \, dV = \phi_e \quad (\text{Gauss' Law})$$

$$\iint_S \vec{B} \cdot d\vec{S} = \iiint_V \rho_m \, dV = \phi_m \quad (\text{Flux Law})$$

How the flux densities (electric  $\vec{D}$ , magnetic  $\vec{B}$ ) and field intensities (electric  $\vec{E}$ , magnetic  $\vec{H}$ ) are related.

For simple (isotropic) materials, we have a simple linear relationship:

$$\vec{D} = \epsilon \vec{E} \text{ [C m}^{-2}\text{]} \quad \text{(Dielectric Material)}$$

$$\vec{B} = \mu \vec{H} \text{ [Wb m}^{-2}\text{]} \quad \text{(Magnetic Material)}$$

$$\vec{J} = \sigma \vec{E} \text{ [A m}^{-2}\text{]}$$

- $\epsilon$  and  $\mu$  are the permittivity and permeability of a given material respectively. For simple (isotropic and homogeneous) materials, these are real numbers.
- At higher frequencies, we need to consider the material polarizability.

- We can extract many material properties from  $\varepsilon$  and  $\mu$ .

The speed of light:

$$c = \sqrt{\frac{1}{\mu\varepsilon}}$$

The characteristic impedance:

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

The refractive index:

$$n = \sqrt{\mu\varepsilon}$$

- Most materials are considered non-magnetic ( $\mu_r = 1$ ).
- Further properties at nanoscale EM

In real life, there are many types of media. Generally,

$$\vec{D}(\vec{r}, t) = \epsilon(\vec{r}) \vec{E}(\vec{r}, t) [\text{C m}^{-2}]$$

Anisotropic materials:

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

The permittivity  $\epsilon$  is a tensor (or matrix) as properties depend on the direction.

For media with loss,  $\epsilon$  is a complex number.

- For dispersive media,  
 $\epsilon = f(\omega)$ .
- Unsuitable for communications
  - Material Dispersion causes pulse spreading
- We compute the dispersion relation for devices such as waveguides.
- However, naturally all materials are dispersive to some extent.

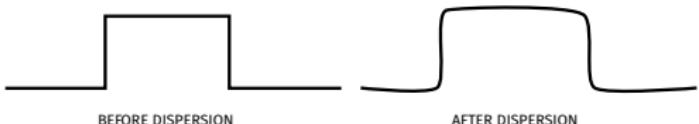


Figure 3: Frequency Dispersion

- Common circuit laws (Ohm's, KCL, and KVL) can be derived from the Maxwell's equations
- All circuit relations can be extracted

$$\vec{J}_c = \sigma \vec{E} \quad \Leftrightarrow \quad i = \frac{1}{R} v_R = G v_R \quad (\text{Ohm's Law})$$

$$\vec{B} = \mu \vec{H} \quad \Leftrightarrow \quad \phi_m = L i_L$$

$$\vec{M} = \mu \frac{\partial \vec{H}}{\partial t} \quad \Leftrightarrow \quad v_L = L \frac{\partial i_L}{\partial t}$$

$$\vec{D} = \epsilon \vec{E} \quad \Leftrightarrow \quad Q = Cv$$

$$\vec{J}_d = \epsilon \frac{\partial \vec{E}}{\partial t} \quad \Leftrightarrow \quad i_C = C \frac{\partial v}{\partial t}$$

$$\oint_C \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t} \iint_S \vec{B} \cdot d\vec{S} = -\frac{\partial \phi_m}{\partial t} \Leftrightarrow \sum v = -\frac{\partial \phi_m}{\partial t} = -L_s \frac{\partial i}{\partial t}$$

$$-V + V_R + V_L + V_C = -L_s \frac{\partial i}{\partial t}$$

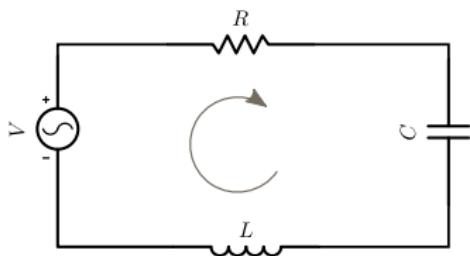


Figure 4: A Simple Circuit

- $L_s = 0$  when circuit dimensions are much smaller than the wavelength ( $\Rightarrow \sum v = 0$ ).

Circuit	Field
Voltage $V$	Electric Field Intensity $\vec{E}$
Current $I$	Magnetic Field Intensity $\vec{H}$
Power $V \times I^*$	Poynting Vector Power Flow $\vec{E} \times \vec{H}^*$

You may have noticed loss of cell-phone reception when inside an elevator or driving through a tunnel.

EM wave propagation is governed by **boundary conditions**.

- We are interested in determining the fields in a given region in space
  - Use the integral forms to derive the boundary conditions
- Boundaries represent discontinuities in field values
  - The derivatives become undefined
- We break the fields into *tangential* and *normal* components

## BOUNDARY CONDITIONS

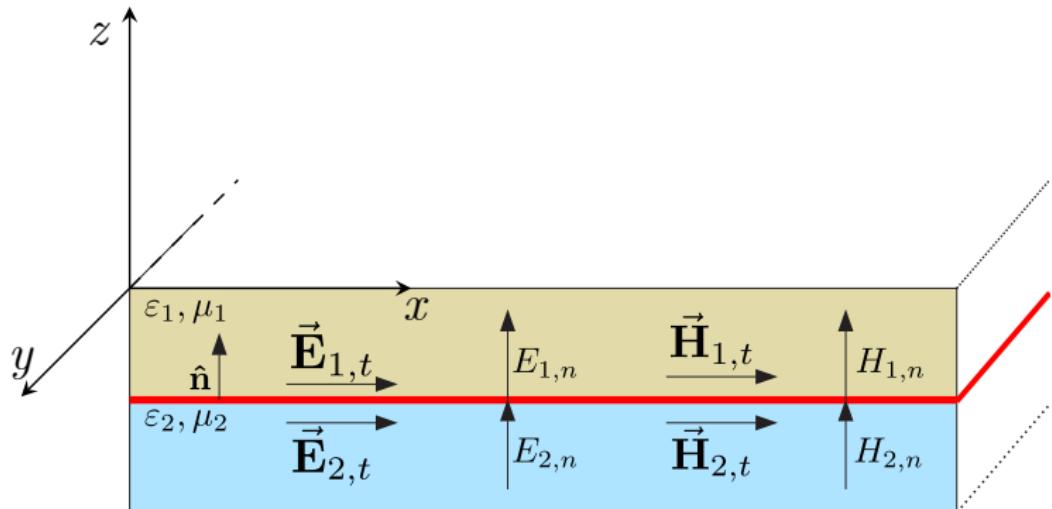


Figure 5: Boundary Conditions at an Interface

- The tangential components of the fields remain continuous along the boundary
- The normal components are discontinuous

$$\hat{\mathbf{n}} \times (\vec{\mathbf{E}}_1 - \vec{\mathbf{E}}_2) = \vec{\mathbf{M}}_s$$

$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{D}}_2 - \vec{\mathbf{D}}_1) = \rho_{e,s}$$

Similarly,

$$\hat{\mathbf{n}} \times (\vec{\mathbf{H}}_1 - \vec{\mathbf{H}}_2) = -\vec{\mathbf{J}}_s$$

$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{B}}_2 - \vec{\mathbf{B}}_1) = \rho_{m,s}$$

- For finite conductivity media ( $\sigma_1, \sigma_2 \neq \infty$ )
  - $\vec{J}_s, \vec{M}_s = 0, \rho_{e,s}, \rho_{m,s} = 0$

$$\hat{\mathbf{n}} \times (\vec{\mathbf{E}}_1 - \vec{\mathbf{E}}_2) = 0$$

$$\hat{\mathbf{n}} \times (\vec{\mathbf{H}}_2 - \vec{\mathbf{H}}_1) = 0$$

$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{D}}_2 - \vec{\mathbf{D}}_1) = 0$$

$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{B}}_2 - \vec{\mathbf{B}}_1) = 0$$

- For one PEC medium ( $\sigma_1 = \infty$ )
  - $\vec{E}_1 = \vec{H}_1 = 0$ , All magnetic sources are zero

$$\hat{\mathbf{n}} \times \vec{E}_2 = 0$$

$$\hat{\mathbf{n}} \cdot \vec{H}_2 = \vec{J}_s$$

$$\hat{\mathbf{n}} \cdot \vec{D} = \rho_{e,s}$$

$$\hat{\mathbf{n}} \cdot \vec{B}_2 = 0$$

- In majority of cases, the time-variance of the fields is sinusoidal (time-harmonic).
- These time variations represented by  $\exp(j\omega t)$
- We replace  $\partial/\partial t$  by  $j\omega$ .

$$\nabla \times \vec{\mathbf{E}} = -j\omega \vec{\mathbf{B}}$$

$$\nabla \times \vec{\mathbf{H}} = j\omega \varepsilon \vec{\mathbf{E}} + \vec{\mathbf{J}}$$

$$\nabla \cdot \vec{\mathbf{E}} = \rho/\varepsilon$$

$$\nabla \cdot \vec{\mathbf{H}} = 0$$

- Wave Equations
- Dielectric Properties and Materials
- Nano-scale Electromagnetics